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PULMONARY FUNCTION AFTER OXYGEN-ACCELERATED DECOMPRESSIONS FROM REPETITIVE SUB-SATURATION AIR DIVES

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To remove personnel from a disabled submarine, rescuers will dive repeatedly with long bottom times and may use oxygen-accelerated decompression. We assessed pulmonary safety after repeated dives using proposed accelerated decompression schedules for 30, 40, or 60 feet of seawater with bottom times of 180, 240, or 360 minutes. Pulmonary function was evaluated within one hour of surfacing from the second dive ("immediate"), and two to four days after the dives ("delayed"). Of 115 divers, 26 had immediate low FEV_1 and 11 had immediate low FVC, but only four showed delayed low FEV_1, and none had delayed low FVC or D_LCO. All changes resolved within one week. Immediate deficits were approximately proportional to oxygen exposure, though with a wide range of magnitude, while delayed changes appeared unrelated to dose. These oxygen exposures caused pulmonary stress with acceptable risk of short-term pulmonary function deficit and no evidence of long-term changes.

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INTRODUCTION

The Submarine Rescue and Diving Recompression System (SRDRS), the future disabled submarine rescue capability for the U.S. Navy, will include a module capable of transporting up to 16 submariners and two operators, and a surface chamber able to accommodate up to 36 people. A total of 10 dives would be required to rescue a 155-man crew. Oxygen-accelerated decompression as part of a repeated-dive profile could permit 10 operators to rescue a fully-manned submarine.

Even emergency-use decompression schedules must keep the overall incidence of DCS within acceptable limits without imposing unacceptably severe symptoms or signs of pulmonary or CNS oxygen toxicity. NEDU was tasked to develop and test oxygen-accelerated decompression schedules for repetitive sub-saturation air sorties.[1] Eight oxygen-accelerated decompression profiles for tenders in a disabled submarine rescue vehicle were tested. Each profile involved two dives of the same duration to the same depth. NEDU Technical Report 05-04[2] describes the development and testing of the decompression profiles, while this report details the oxygen toxicity observed during testing of the profiles.

METHODS

GENERAL

Fifty-seven divers completed 125 pairs of dives in the Ocean Simulation Facility (OSF) at Navy Experimental Diving Unit (NEDU), Panama City, FL. Each dive profile consisted of two dives of identical bottom time in the dry chamber separated by a surface interval of similar duration outside of the chamber. Divers breathed air during compression and on the bottom, but breathed 90-100% oxygen during most of decompression. Bottom times were 3, 4, or 6 hours at depths of 30, 40, or 60 feet of sea water (fsw). To simulate a rescue operation somewhat more closely, divers exercised for the first 40 minutes on the bottom and for 20 minutes immediately before decompression. The exercise consisted of 5 alternating arm-curls with 10-lb weights, one group every 5 minutes.

Divers used the MBS 2000 closed-circuit Hyperbaric Oxygen Treatment Pack (HOTP) system[3] to support oxygen breathing requirements of the decompressions. After every 60 minutes of oxygen breathing on the system, they breathed chamber air for a 15-minute air break. The MBS 2000 HOTP systems had been fitted with sampling ports on the inspiratory side, and oxygen fraction was monitored using a mass spectrometer (EXTREL, Pittsburgh PA). When oxygen fraction fell below about 85%, divers were instructed to purge the system with oxygen. The CO_2 absorbent canisters were packed with 408 mesh Sofnolime®, (Molecular Products, Thaxed, Essex, UK), each with 1.750 ± 0.02

kg (3.85 ± 0.044 lbs). Carbon dioxide fractions in inspired gas also were monitored, but no interventions were needed.

The dive profiles are summarized in Table 1, and the approximate Unit Pulmonary Toxic Dose (UPTD) for each profile, calculated using the linear formula[4], is given in Table 2. UPTD calculations do not account for recovery between dives.

The dive profiles are numbered in order of increasing total dive time. In order of depth first and bottom time second, profiles 3 and 6 went to 30 fsw, profiles 1, 4, and 7 to 40 fsw, and 2, 5, and 8 to 60 fsw. However, in order of increasing UPTD, the sequence is profile 3, 1, 6, 4, 7, 2, 5, and 8.

Table 1: Dive profiles for disabled submarine rescue simulation

Profile #	Depth (fsw)	Bottom Time (min)	Total Stop Time (min)	Total Time Dive (min)	Total Time Profile (min)	Profile #	Depth (fsw)	Bottom Time (min)	Total Stop Time (min)	Total Time	Total Time Profile (min)
1	40	180	52	238		5	60	240	172	420	
	0	127					0	66			
	40	180	99	285	650		60	240	195	443	929
2	60	180	122	308		6	30	360	90	462	
	0	56					0	269			
	60	180	169	355	719		30	360	102	474	1205
3	30	240	43	291		7	40	360	131	503	
	0	196					0	228			
	30	240	82	330	817		40	360	159	531	1303
4	40	240	94	342		8	60	360	232	604	
	0	145					0	126			
	40	240	103	351	838		60	360	251	623	1353

Decompression to the first stop and between stops was at 30 fsw/min.

Table 2: Oxygen exposures (UPTD) for decompression

Profile	UPTD	n	Profile	UPTD	*n*
1	254	16	5	806	16
2	631	15	6	261	8
3	177	16	7	460	16
4	338	14	8	1068	16

n = the number of subjects for whom pulmonary function was measured after surfacing.

EXPERIMENTAL DESIGN AND ANALYSIS

The subjects performed pulmonary function tests one to five days before the test dives (baseline), immediately before diving, within 90 minutes of leaving the chamber after the second dive, and on the second or fourth day after the test dives. Each pulmonary function measurement session involved three successful repeats of each test, according to the American Thoracic Society standards.[5] The average values from the three trials were used in all further analysis.

We studied forced vital capacity (FVC), forced expired volume in one second (FEV_1), and diffusing capacity (D_LCO) corrected for hemoglobin concentration. Flow volume loops were measured on each occasion, and diffusing capacity was measured at baseline and at the later post-dive session. The baseline average values were used to assess changes in diffusing capacity, and the averages of baseline and immediate pre-dive measurements were used to assess changes in flow-volume loop parameters. In the NEDU population, 95% confidence limits have been found to be ±7.7% on FVC, ±8.4% on FEV_1, and ±14.2% on D_LCO.[6] A post-dive pulmonary function measurement was considered to be depressed if it fell below these limits. Any pulmonary function test that showed a value significantly depressed at the second pulmonary function measurement was repeated approximately one week after the dive.

Divers were questioned about specific symptoms (Table 3) at air breaks, between dives, and at each pulmonary function measurement session.

Table 3: Symptoms list

During the dives:	After the dives:
Vision changes	Inspiratory burning
Ringing or roaring in ears	Cough
Nausea	Chest pain or tightness
Tingling or twitching	Shortness of breath
Light-headedness or dizziness	Lowered exercise tolerance
Chest tightness	Unreasonable fatigue
Shortness of breath	
Rapid shallow breathing	
Burning on inspiration	
Cough	

EQUIPMENT AND INSTRUMENTATION

The Collins CPX and Collins GS Modular Pulmonary Function Testing System instruments (W. R. Collins, Inc.; Braintree, MA) were used to measure pulmonary function. A CO-oximeter (Instrumentation Laboratory; Lexington, MA) determined carboxyhemoglobin and hemoglobin concentrations in venous blood.

PULMONARY FUNCTION PROCEDURES

Baseline flow volume loops and diffusing capacity were recorded several days before diving. After subjects surfaced from the first dive they were asked about symptoms but pulmonary function was not measured. After they surfaced from the second dive, they were asked again about symptoms and flow volume loops were recorded. At the pulmonary function session two to four days later, flow volume loops and diffusing capacity were measured and divers were asked again about symptoms.

To record flow volume loops, a subject wearing nose clips breathed on a mouthpiece into and out of a spirometer. The subject first breathed normally, then inhaled rapidly and as fully as possible before exhaling with maximum force, and then inhaled fully. Measurements of FVC, FEV_1, peak expired flow, and other variables were read from the flow volume loops.

The single-breath technique was used to measure D_LCO: the subject exhaled as far as possible, inhaled a large breath of test gas from the spirometer, held his breath for 10 seconds, then exhaled rapidly past the analyzer probe. The test gas contained 0.3% carbon monoxide and 0.3% methane, and the variables used to obtain D_LCO were calculated from the gas concentrations before and after the breath-hold. Adjustments were made for carboxyhemoglobin and hemoglobin concentrations.[7] Volumes expired before the gas concentrations were measured and the volumes of gas over which the concentrations were averaged were adjusted to ensure that the analyzer signal was stable when measurements were recorded.[8]

RESULTS

Non-respiratory symptoms

Four divers reported nausea during decompression, three during profile 8 after breathing oxygen at 50 fsw (1068 UPTD) and one during profile 7 (460 UPTD) after 44 minutes of oxygen at 30 fsw and about 15 minutes of oxygen at 20 fsw. Three subjects, one of whom had been nauseated, reported fatigue, low exercise tolerance, and/or difficulty sleeping after profile 8. One subject reported unreasonable fatigue after profile 3 (177 UPTD), and one reported low exercise

tolerance after profile 5 (806 UPTD), while one subject, not the one who was nauseated, reported low exercise tolerance and difficulty sleeping after profile 7.

Pulmonary effects

Although pulmonary symptoms were reported after 24 man-dives, most were mild. Moderate to severe symptoms were reported after profile 2 (UPTD = 631), profile 5 (UPTD = 806) and profile 8 (UPTD = 1068), some with and some without changes in pulmonary function. Symptoms sometimes persisted for several days (Fig.1), often after associated changes in pulmonary function had resolved. All symptoms had cleared by one week after diving.

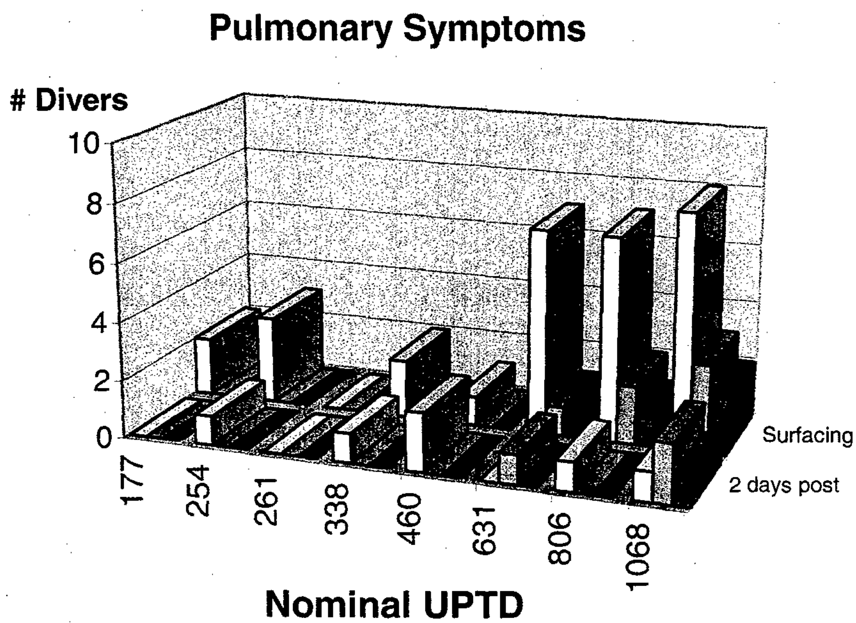

Figure 1: Pulmonary symptoms as a function of UPTD.
Symptom grading: Yellow = mild, orange = moderate, and red = moderately severe to severe.

Flow-volume loops after surfacing were recorded for 115 subject dives. At least one parameter was significantly below baseline in 34 of the recordings. However, after two to four days, only five of the 122 subjects measured showed depressed pulmonary function parameters, and by one week after diving all divers had recovered. Changes for all subjects are shown in Figures 2-6.

Although greater oxygen dose (UPTD) was associated loosely with more reduction in flow-volume parameters on surfacing, many divers experienced no significant changes, and some had increases in measured pulmonary variables.

Diffusing capacity, measured only at the later session, was within normal limits of baseline for all measurements. Late deficits in pulmonary function did not appear to be associated with UPTD.

The most severe reductions recorded after surfacing were 16.4% in vital capacity after profile 8, with mild symptoms; 17.8% in FEV_1 and –29.6% in mid-expiratory flow after profile 5, with mild inspiratory burning; and –26.1% in peak expiratory flow with mild symptoms after profile 8. A notable change in pulmonary function was found after profile 1, also, when mid-expiratory flow from one diver was reduced by 31% from the baseline and pre-dive values, accompanied by mild chest tightness.

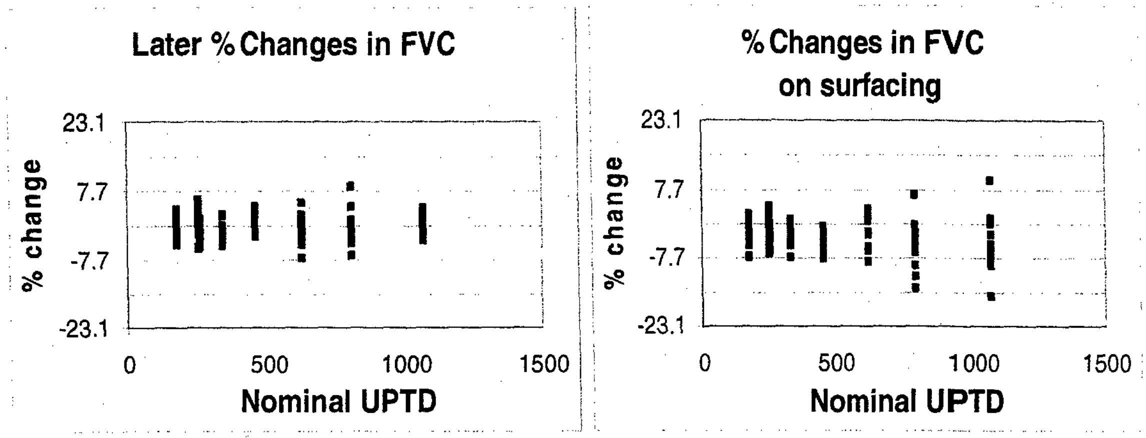

Figure 2: Forced vital capacity changes from the average of baseline and immediate predive measurements. The scale has been chosen in bands of 95% confidence interval. The 95% confidence interval around baseline is ±7.7%.

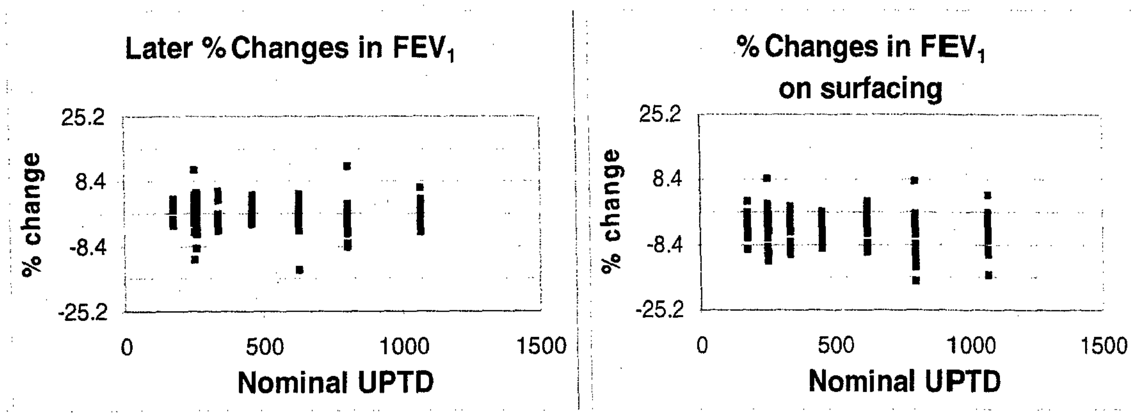

Figure 3: FEV_1 changes from the average of baseline and immediate predive measurements. The 95% confidence interval is ±8.4%.

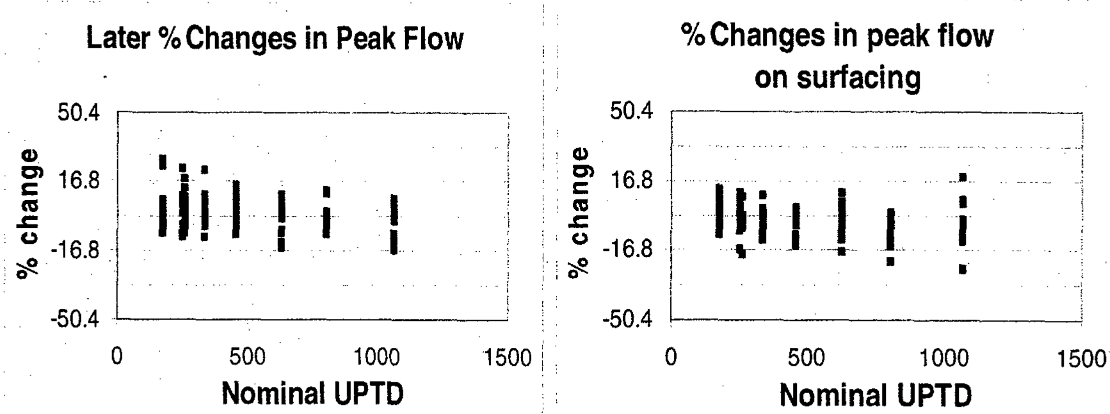

Figure 4: Peak expiratory flow changes from the averages of baseline and immediate pre-dive measurements. The 95% confidence interval for peak expiratory flow is ±16.8%.

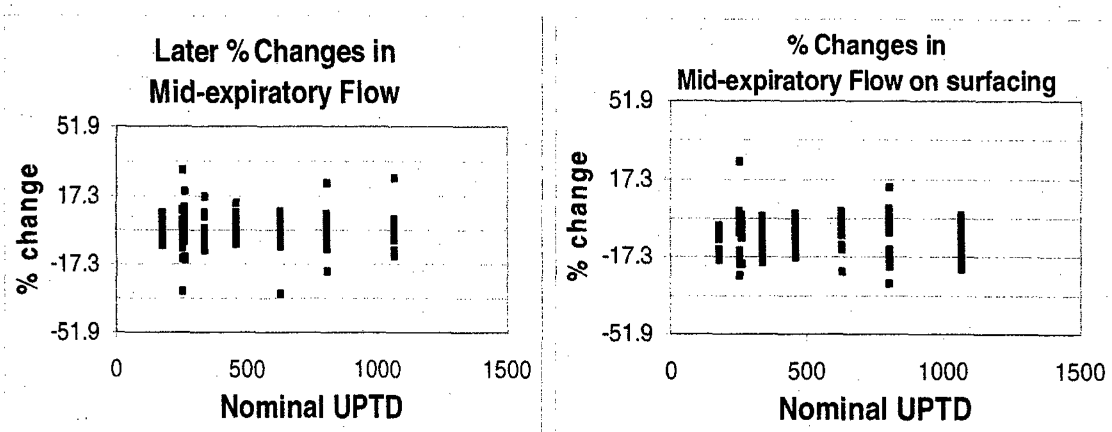

Figure 5: Mid-expiratory flow (25% to 75% of forced expired volume) changes from the averages of baseline and immediate pre-dive measurements. The 95% confidence interval for peak expiratory flow is ±17.3%.

Later % Changes in D_LCO

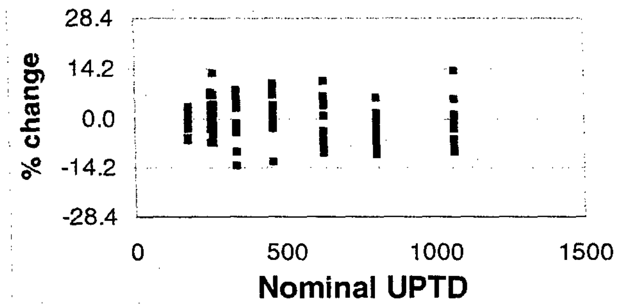

Figure 6: Diffusing capacity changes from baseline measurements. Diffusing capacity was measured only at baseline and two to four days after surfacing. The 95% confidence limits are ±14.2%.

DISCUSSION AND CONCLUSIONS

The nausea reported during decompression may have been caused by oxygen exposure, but also could have resulted from prolonged breathing of air warmed by passage through the MBS 2000 scrubber unit. However, recorded inspiratory gas temperatures rarely exceeded 35ºC. The fatigue and difficulty sleeping also may have been related to CNS oxygen toxicity, but may just as well have been caused by the disruption of diurnal rhythms caused by the long profiles plus pre- and postdive testing – even the relatively-short profile 3 was 13 hours long, and profiles 7 and 8 were longer than 20 hours.

The highest oxygen exposures – longest and deepest – in the short term caused significant pulmonary distress in a number of divers. However, divers were not incapacitated and they recovered quickly. From the standpoint of oxygen toxicity, these profiles are acceptable for the emergency use for which they were developed.

REFERENCES

1. Naval Sea Systems Command letter, *NAVSEA 00C Task Assignment 01-10: Submarine Rescue Decompression and Tender Management*, 10560/TA 01-10 Ser 00C32/3035 of 14 Feb 01

2. W.A. Gerth. Oxygen-Accelerated Decompression of Submarine Rescue and Diving Recompression System (SRDRS) Operators and Tenders. NEDU Technical Report 05-04, Navy Experimental Diving Unit, Panama City, FL, 2005.

3. D.D. White, D.M. Fothergill, D. Warkander, and C. Lundgren. Submarine Rescue System – Hyperbaric Oxygen Treatment Pack. NSMRL Report 1215, 2000.

4. A.L. Harabin, L.D. Homer, P.K. Weathersby, and E.T. Flynn. An analysis of decrements in vital capacity as an index of pulmonary oxygen toxicity. J. Appl. Physiol. 63(3): 1130-1135, 1987.

5. American Thoracic Society, "Standardization of Spirometry 1994 Update," *American Journal of Respiratory and Critical Care Medicine*, Vol. 152 (1995), pp. 1107–1136.

6. B.E. Shykoff, Pulmonary Effects of Submerged Breathing of Air or Oxygen, NEDU TR 02-14, Navy Experimental Diving Unit, Nov 2002.

7. Instruction Manual for the Collins Comprehensive Pulmonary Laboratory (CPL) (Braintree, MA: Collins Medical, 2000).

8. B.E. Shykoff, *Measurement of Diffusing Capacity for Carbon Monoxide (D_LCO)*, NEDU TR 02-04, Navy Experimental Diving Unit, May 2002.